(12) # EUROPEAN PATENT APPLICATION

(71) Applicant: **GEONICS LIMITED**
1745 Meyerside Drive
Mississauga Ontario, L5T 1C5(CA)

(72) Inventor: **McNeill, James Duncan**
44, Longwood Drive
Don Mills Ontario, M3B 1T8(CA)

(72) Inventor: **Kaufman, Alexander Arkadievich**
21676 West 15th Place
Lakewood Colorado 80215(US)

(74) Representative: **Newby, John Ross et al,**
J.Y. & G.W. Johnson Furnival House 14/18 High Holborn
London WC1V 6DE(GB)

(54) Electromagnetic geophysical surveying apparatus and system.

(57) A frequency domain geophysical electromagnetic surveying system is provided in which intermittent primary fields having sharp terminations are generated in a cycle having a fundamental frequency by a transmitter (8), and a receiver (14) includes a gate (22) passing only secondary signals received during interruptions of the primary field, the gated signal being applied to filters (24, 25) turned to harmonics of the predetermined frequency. The filter outputs are synchronously demodulated (26I, 26Q, 28I, 28Q) to provide signals corresponding to at least the in-phase component of the secondary signal at the fundamental frequency, and preferably in-phase and quadrature components at at least two harmonics. The system can provide improved resolution particularly of the characteristics of inphase secondary signals received from terrain being surveyed.
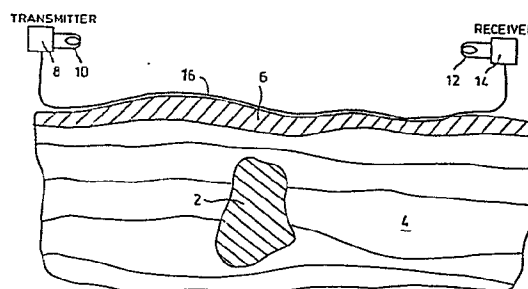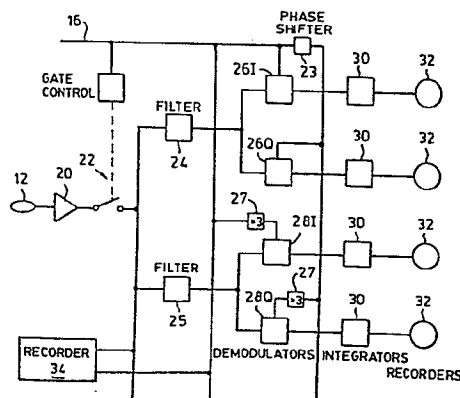
FIG. 1

FIG. 2

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ELECTROMAGNETIC GEOPHYSICAL SURVEYING
APPARATUS AND SYSTEM.

This invention relates to geophysical electro-
magnetic surveying systems.

In such systems, terrain to be surveyed is
subjected to a primary electromagnetic field, and measure-
5   ments are made of signal currents induced in a receiver by
secondary magnetic fields generated by current induced in
the terrain by the primary magnetic field. The secondary
magnetic field, in practical situations, comprises (assum-
ing an alternating primary field) components both in phase
10 with and in quadrature with the primary field. A problem
with all such systems is that the primary field is very
large compared with the secondary field, which leads to
difficulty in isolating the desired secondary signals.
One approach to these problems in techniques of the
15 frequency domain type, in which both a transmitter which
generates the primary field and the receiver are operated
at one or more defined frequencies is to provide a
receiver in which the received primary signal is cancelled
so as to leave only the desired secondary signals. Such
20 cancellation arrangements, if effective, are usually com-
plex and/or critically dependent on the maintenance of a
predetermined geometrical relationship between a
transmitter of the primary signal and the receiver.
Slight variations in this geometry, which are to some

degree inevitable, produce inaccuracies of cancellation
which show up as noise in the received signal. These
problems are of course most serious in relation to the
in-phase component of the secondary signal. All of these
5   problems are aggravated by the fact that for most purposes
it is desirable to use frequencies that are as low as
possible, which still further reduces the relative
magnitude of the secondary signal.

An alternative approach has been to utilize
10   so-called transient techniques, in which the primary field
is interrupted at intervals, and the secondary field is
sampled at intervals during these interruptions. Since
the primary field is absent during the measurements, the
problems associated with cancellation are avoided, and the
15   equivalent of low frequency observations can be achieved
merely by sufficiently delaying sampling of the transient
signal, but the available secondary signal components are
of relatively smaller magnitude, and become increasingly
smaller the longer sampling is delayed, thus again
20   impairing signal-to-noise ratios. It has also been widely
believed that such transient techniques only provide data
as to the quadrature components of the secondary signal,
upon the reasoning that any primary component would be in
phase with the primary signal, and thus since no
25   measurements are made in the presence of the primary
signal, no measurements are made of the in-phase component
of the secondary signal. Whilst this reasoning is
fallacious, it is true that known transient techniques
fail to discriminate between the in-phase and quadrature
30   components of the secondary signal.

A characteristic of transient systems is that
they are essentially broadband in nature since the
response will contain components extending through the
frequency spectrum. This of course implies a broadband

receiver so that decay of the transient secondary signal
can be observed for long enough to enable its information
content to be exploited. This characteristic also is
associated with noise problems.

5   In his paper "Resolving Capabilities of the
Inductive Methods of Electroprospecting" published in
Geophysics, Vol. 43, No. 7 (December 1978), pages
1392-1398, one of the inventors discusses the relative
theoretical resolving powers of the frequency domain and
10 transient methods, in terms of their capability of
distinguishing wanted signals from geological noise. In
that paper, he concluded that for multispectral frequency
domain systems excellent rejection of the effects of
geological noise could be achieved by measuring the low
15 frequency in-phase components of the received signal but
that, since these are of low amplitude, this is difficult
to carry out for the reasons given above.

       A primary objective of the invention is to
provide improved recovery of in-phase secondary signals in
20 a frequency domain system.

       A further objective of the present invention is
to provide a frequency domain method which renders it
practical to resolve higher order terms of the expansions,
both for the quadrature and in-phase components. This
25 makes it possible to resolve successive signal components
which are proportional to odd and even powers respectively
of the conductivity of terrain features, thus substantial-
ly increasing the capability of the system for resolving
signals from features of different conductivities.

30   According to the invention, apparatus is
provided for processing signals from a geophysical
electromagnetic survey of the type in which terrain to be

surveyed is subjected to a primary magnetic field by a
transmitter energized by a cyclical current waveform such
that the field is subject to abruptly commencing interrup-
tions at regular intervals, and a receiver produces

5   secondary signals corresponding to current induced at the
receiver during the interruptions by transient secondary
fields induced in the terrain by the abrupt commencement
of the interruptions, the apparatus being configured to
process only such secondary signals as occur during

10 regular predetermined intervals within the interruptions,
together with a reference signal in synchronism with said
cyclical current waveform, and to apply such secondary
signals to a narrow band filter tuned to accept the funda-
mental frequency of the cyclical current waveform, the

15 output of the filter together with said reference signal
being applied to a first synchronous detector which
detects the filter output in relation to the phase of the
primary current waveform on a detection axis adjusted to
provide any phase compensation necessary for the periods

20 in which the secondary signal is not processed, whereby to
recover at least the in-phase component of the secondary
signal at said fundamental frequency. Preferably, the
apparatus includes further filters and synchronous
detectors so as to isolate both in-phase and quadrature

25 phase components of the secondary signal at at least two
harmonic components of the primary signal frequency, one
of which may be the fundamental. Although it is
acknowledged that the quadrature phase signal component
can be extracted in the presence of the primary field it,

30 too, is more easily processed in the absence of the
primary field since, for example, small errors in phase do
not then lead to large errors in the quadrature phase
component.

Further features of the invention will be
35 apparent from the following description of an exemplary

embodiment of the invention with reference to the
accompanying drawings, in which:

Figure 1 is a diagrammatic representation
showing a geophysical surveying system located above
5   terrain to be surveyed;

Figure 2 is a block diagram showing essential
features of the receiver shown in Figure 1; and

Figure 3 is a diagram illustrating current
waveforms present at various points in the system.

10   Referring to Figure 1, terrain to be surveyed is
shown in cross section, formations shown being a conduc-
tive ore body 2, possibly conductive host rock 4 and
possibly conductive overburden 6. A transmitter 8 ener-
gizes a transmitter coil 10 to generate a primary magnetic
15   field, whilst a receiver coil 12 picks up signals induced
by primary and secondary fields and applies them to a
receiver 14. A cable 16 transmits a reference signal from
the transmitter to the receiver. Other equivalent means
such as a radio link, or quartz crystal oscillators synch-
20   ronized to a common reference may also of course be used
if desired. All of the formations will give rise to
secondary signals which may be received by an electro-
magnetic surveying system and which are rather difficult
to differentiate, although only signals from the ore body
25   will normally be of interest, the remaining signals being
merely "geological noise". Moreover, since the ore body
is the formation most distant from the surveying system,
its signals may well be the weakest, particularly if it is
deeply buried. On the other hand, whilst the response of
30   each formation is frequency dependent, the nature of this
dependency and the phase of the response is influenced by
parameters of the formation, notably its conductivity and
configuration.

In order to provide the system shown in Figure 1
with the capabilities which are the object of the present
invention, the transmitter 10 and coil 12 are arranged to
generate a discontinuous magnetic field such as is shown
5   in line A of Figure 3, which illustrates the current
waveform in the transmitter coil. This current also
determines the primary field strength. This waveform is
similar to that used in some transient systems, comprising
regular rectangular current pulses of alternate polarity
10 separated by off periods, in a repeated cycle of known
frequency. Typically, this frequency will be in the order
of 25-100H$_z$, frequencies corresponding to the fundamental
of harmonics of the local power supply frequency being
avoided. Thus in areas with a 60H$_z$ supply frequency, a
15 frequency of 90 or 30H$_z$ may be selected.

The response at the receiver coil will also be
similar to that characteristic of transient systems, being
a series of decaying pulses as shown in line B of Figure
3. The duration and configuration of the primary current
20 cycle is such that each pulse has decayed substantially to
zero before commencement of the next pulse.

It should be understood that the exact
configuration of the primary waveform is not critical to
the invention, as long as it exhibits abrupt termination
25 of the current flow at regular intervals, each termination
being preceded by a sufficient period in which the current
is changing sufficiently slowly for any secondary field to
have diminished substantially to zero, and followed by a
sufficient period in which the current is zero for any
30 secondary field resulting from the termination to diminish
substantially to zero. The current prior to termination
may either always be in the same direction, or in alter-
nate directions. In the latter case there will be two
terminations in each cycle of the fundamental repetition
35 frequency. Termination of the primary current should be

sufficiently abrupt to avoid attenuation of any harmonics
likely to produce secondary signals of interest. Trans-
mitters and transmitter coils intended for transient
systems are suitable for use in the present invention as
5   long as they can generate appropriate waveforms in a cycle
of predetermined frequency. The receiver 14 (see Figure
2) accepts the pulses picked up by the coil 12 and sub-
jects them to broadband amplification in a pre-amplifier
20. They are then subjected to gating by a switch or
10   transmission gate 22 synchronized with the primary signal
so as to pass signals only for intervals wholly within the
periods when no current is flowing in the transmitter
coil. The effect of this gating is to eliminate signals
received whilst current is passing in the transmitter
15   coil, thus leaving only those pulses following termination
of current flow in the primary, these representing solely
the response to the secondary field during the on times of
the gate. Thus far the receiver is again similar to that
used in many transient systems.

20   The switched signal, either direct from the
switch 22 or from the recording device 34 is then applied
to a series of narrow band filters of which the first two
filters 24, 25 are shown. The filters are tuned to the
fundamental and odd harmonics of the primary signal
25   frequency so as to resolve the components of the secondary
response attributable to each of these harmonic com-
ponents. The outputs of the filters are then subjected to
synchronous detection on the in-phase and quadrature axes
using a reference signal derived from that on cable 16 or
30   recorded by device 34. To take account of the deletion of
parts of the received signal for the transmitter current
waveform shown in Figure 3A the phase of the reference
signal is shifted so that the in-phase component of the
received signal (the sine component of the Fourier series)
35   is measured with the received signal located in time as

shown in lines C and D of Figure 3. Such correction is
not necessary if the primary waveform is unipolar. The
phase of the reference is then shifted a further 90° by
phase shifter 23 to derive a quadrature phase reference so
5   as to measure the cosine term. The in-phase and
quadrature reference signals are applied directly to
in-phase and quadrature demodulators 26I and 26Q receiving
inputs from filter 24 so as to yield rectified DC output
signals proportional to the fundamental in-phase and
10 quadrature phase components of the signal shown in Figure
3C. The same reference signals, after having been
frequency multiplied by three in multipliers 27 are
applied directly to in-phase and quadrature phase
demodulators 28I and 28Q, receiving inputs from filter 25
15 (also tuned to the third harmonic) if the in-phase and
quadrature phase components of the signal at the third
harmonic are desired. In the same way the in-phase and
quadrature phase components at any other harmonic
frequency are obtained. The harmonic components utilized
20 are not necessarily the fundamental and odd harmonics,
depending on the primary current waveform. If this
waveform is rich in even rather than odd harmonics, then
it may be preferred to recover and demodulate the former
in addition to the fundamental.

25   The demodulator outputs are applied to integra-
tors 30 and thence to indicators or recorders 32 or to
further processing circuitry. The outputs may be utilized
in various ways so as to exploit the capability of the
invention to resolve the in-phase components of the
30 secondary signal whilst its capability of providing read-
ings at several frequencies simultaneously may permit
further data relating to terrain structure to be resolved.

In the simplest form of interpretation, the
in-phase output of the fundamental frequency of the

primary field is studied. As compared with a conventional frequency domain system operating at the same frequency and as discussed further below, noise due to changes in system geometry or imperfect cancellation of the primary signal is eliminated. These factors normally limit the lowest frequency at which such systems can be used, since the amplitude of the wanted secondary signal is proportional to the square of the frequency. The present invention further renders the separation of the transmitter and receiver coils non-critical; indeed the coils may be co-located, or even the same coil may be utilized since the secondary signal is never required when the primary current is present. Proximity of the transmitter and receiver coils improves the accuracy with which terrain features of interest may be located.

In an alternative form of interpretation, the various outputs are simply compared after applying an amplitude correction factor to compensate for the different frequencies to which the outputs relate. Assuming for example that the output signal is due essentially to a buried ore body of high conductivity, and an overburden of lower conductivity, the relative contribution to the signal due to the ore body will be different in the various output signals. Thus at low frequencies as between the outputs derived from the frequency component at any one harmonic, each contribution to the quadrature response will be in direct proportion to the conductivities of the ore body and the overburden respectively, in each case multiplied by a factor dependent inter alia upon the location, dimensions and configuration of the body and overburden relative to the position or positions of the transmitter and receiver. In the case of the in-phase response, each contribution will however be in proportion to the square of the respective conductivities. The relative contribution of the higher

conductivity body will decrease in the signals derived
from the higher harmonics, but these signals can
nevertheless be of importance, as will be apparent from
the following discussion.

5   Considering now the outputs derived from the
third harmonic as compared to the fundamental frequency,
each pair of outputs may of course be compared in the same
way, but preferably for the case of the in-phase
components the third harmonic outputs are subtracted from
10   the fundamental frequency outputs after appropriate
adjustment of their relative amplitude to eliminate
frequency dependent amplitude differences. In the case
under consideration, the third harmonic signals are
divided by 9: this correction may be applied if desired by
15   an attenuator network associated with the integrator 30.
In the resulting difference signals, the difference
between responses due to terrain features of different
conductivities will be further emphasised. This
procedure may be repeated for outputs derived from the
20   fifth harmonic, and theoretically, can be repeated
indefinitely, but a practical limit will be set by signal
noise and processing inaccuracies. A similar approach can
be applied to the quadrature phase components.

     It will be appreciated therefore that the system
25   of the invention provides a means which assists in
differentiating the contribution to the secondary signal
of a terrain feature of high conductivity from contribu-
tions due to features of lower conductivity, even when the
signals from such latter features, because of proximity to
30   the point of observation orientation and/or large physical
extent, would normally mask wanted signals from the high
conductivity feature if the latter is deeply buried. The
extent to which this emphasis can be achieved during sig-
nal processing is clearly highly dependent upon the extent
35   to which the wanted signal is otherwise influenced by

noise, and in this respect the present invention
demonstrates important advantages relative to the
conventional frequency domain systems.

The portion of the secondary signal which is
processed is generated in the absence of the primary
signal. This distinguishes the present invention from
known frequency domain systems in which the secondary
signal is measured in the presence of the primary signal.
Although cancellation techniques may be used to tackle
this problem, such techniques are noise prone, and noise
so introduced limits the value of the measurements
particularly of the in-phase component of the secondary
signal. This is unfortunate, since as has been explained
above, the in-phase component will contain a relatively
larger contribution from highly conductive features.

As a further advantage, the absence of the
primary signal during measurement means that the
separation of the transmitter and receiver coils is
non-critical and may be small, a particular advantage in
airborne systems.

As compared with transient systems, the present
invention has the advantage of being narrow-band, thus
facilitating noise rejection. Although it might seem that
the rejection, by the switching technique of the present
invention, of half of the available secondary signal
information would be detrimental, in fact the amplitude of
the output signals is reduced only by a factor of 1/2, and
since the noise level due to spherics and other external
sources is reduced by a similar amount, the loss is mainly
compensated, whilst all noise derived from the primary
signal is wholly rejected.

The conventional approach to overcoming external
noise problems in transient systems has been to increase

the power of the transmitter on the one hand, and to combine the readings from multiple transients on the other hand. Both these solutions create problems, either through bulk and power consumption or slowness of response, particularly when the survey equipment is to be used in airborne applications. The present invention provides the potential of enabling features of interest to be resolved more rapidly and/or with lower transmitter power, and thus is particularly advantageous in airborne and portable systems.

Existing transient systems can in many cases be utilized to provide signals for use in a frequency domain system in accordance with the invention by utilizing the signal processing circuits described above. Thus known equipment may be utilized to generate signals which are stored on a recorder 34 for later analysis. The recordings consist of the wanted secondary signals on one channel together with a second channel carrying a reference signal determinative of the time of the primary signal. In some cases data available on the secondary signal channel may be used to recover the required reference signal.

Although the signal processing circuits and in particular the filters 24,25 and the demodulators 26I, 26Q, 28I, 28Q may be implemented conventionally by analogue circuitry, it may be preferred to digitize the secondary signal data and use digital filtering and demodulation techniques which may be conveniently implemented utilizing a suitably programmed microprocessor. Moreover, if the secondary signal data is recorded, the data need not be processed in real time, and the frequencies utilized may be shifted as desired typically upwards to provide more rapid processing. From the signal processing point of view, however, the functions achieved will be those described above.

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Whilst the invention has been described with particular reference to surface and airborne surveys, it is equally applicable to data from borehole surveys. In such surveys, the in-phase signals recovered by the method of the invention, are diagnostic of conditions at a greater distance from the hole as compared to quadrature signals obtained with conventional techniques, thus increasing the effective exploration radius for each hole.

For the avoidance of misunderstanding, the terms "in-phase signal" and "in-phase component" used in this disclosure and in the appended claims refer to signals and signal components induced by the in-phase component of the secondary field, without necessarily implying that a particular phase relationship to the primary field is maintained during processing.

CLAIMS

1.   Apparatus for processing signals from a geo-
physical electromagnetic survey of the type in which
terrain to be surveyed is subjected to a primary magnetic
field by a transmitter energized by a cyclical current
waveform such that the field is subject to abruptly
commencing interruptions at regular intervals, and a
receiver produces.secondary signals corresponding to
current induced at the receiver during the interruptions
by transient secondary fields induced in the terrain by
the abrupt commencement of the interruptions, characteris-
ed in that the apparatus is configured to process only
such secondary signals as occur during regular predeter-
mined intervals within the interruptions, together with a
reference signal in synchronism with said cyclical current
waveform, and to apply such secondary signals to a narrow
band filter (24) tuned to accept the fundamental frequency
of the cyclical current waveform, the output of the filter
together with said reference signal being applied to at
least a first synchronous detector (26I) which detects the
filter output in relation to the phase of the primary
current waveform on a detection axis adjusted to provide
any phase compensation necessary for the periods.in which
the secondary signal is not processed, whereby to recover
the in-phase component of the secondary signal at said
fundamental frequency.

2.   Apparatus according to claim 1, characterised in
that it includes a second synchronous detector (26Q)
receiving said filter output and said reference signal and
which has a detection axis in quadrature with that of the
first synchronous detector whereby to receive the quadra-
ture phase component of the secondary signal at said
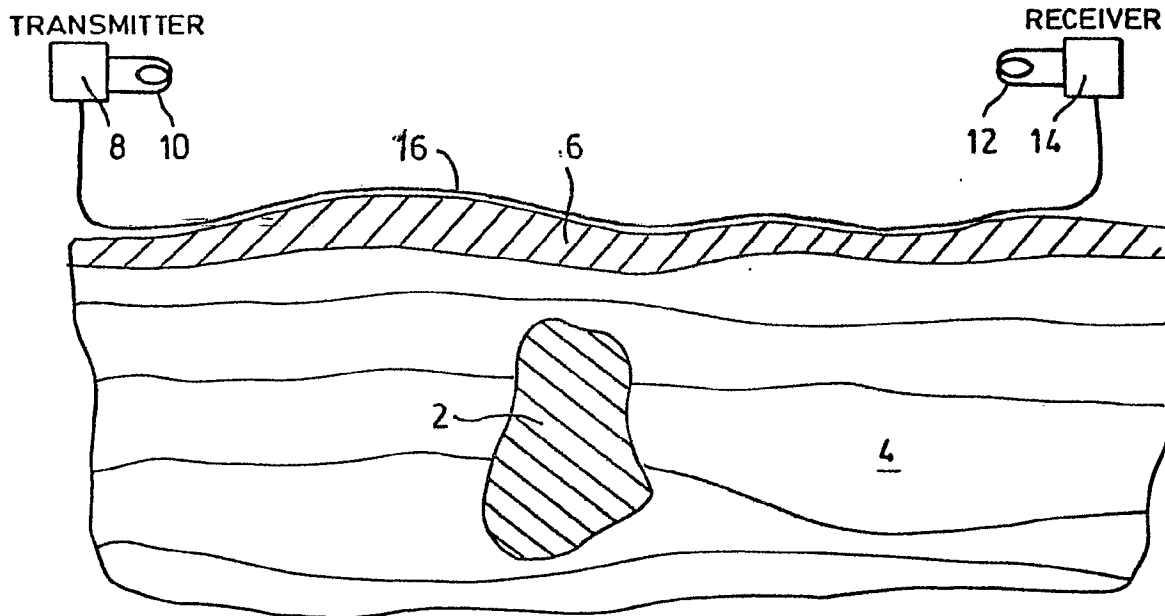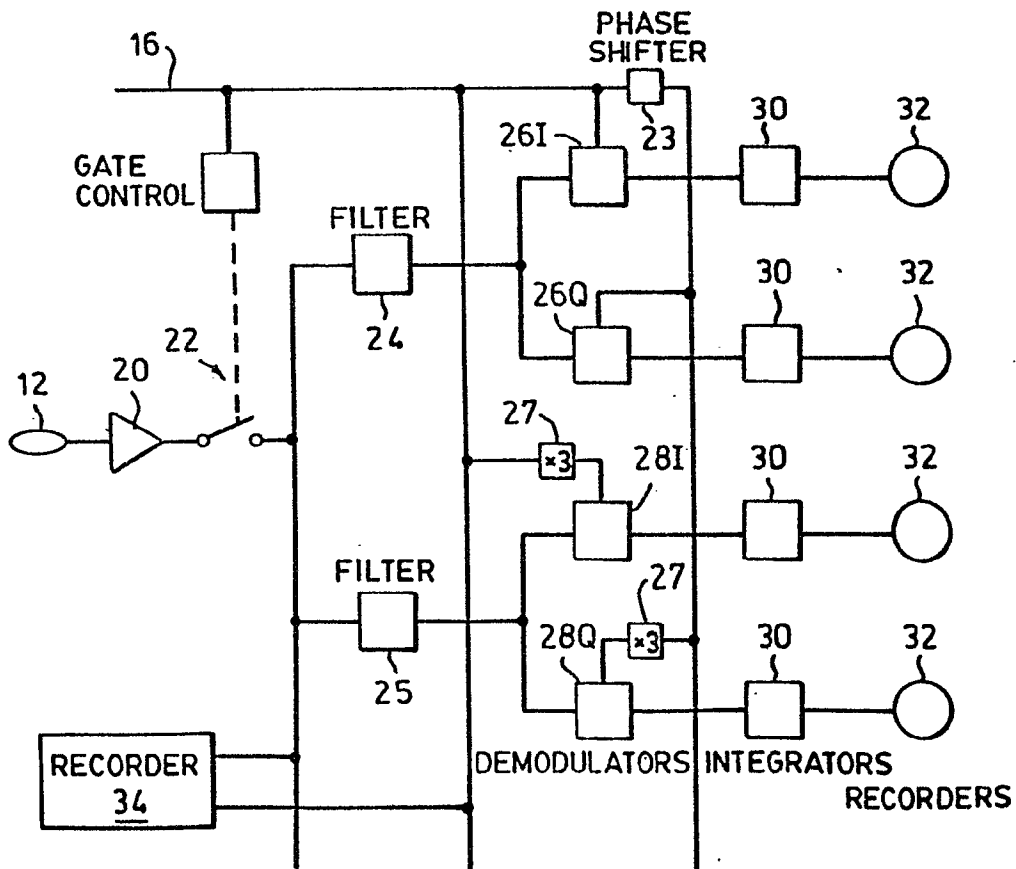fundamental frequency.

3.   Apparatus according to claim 1, further includ-
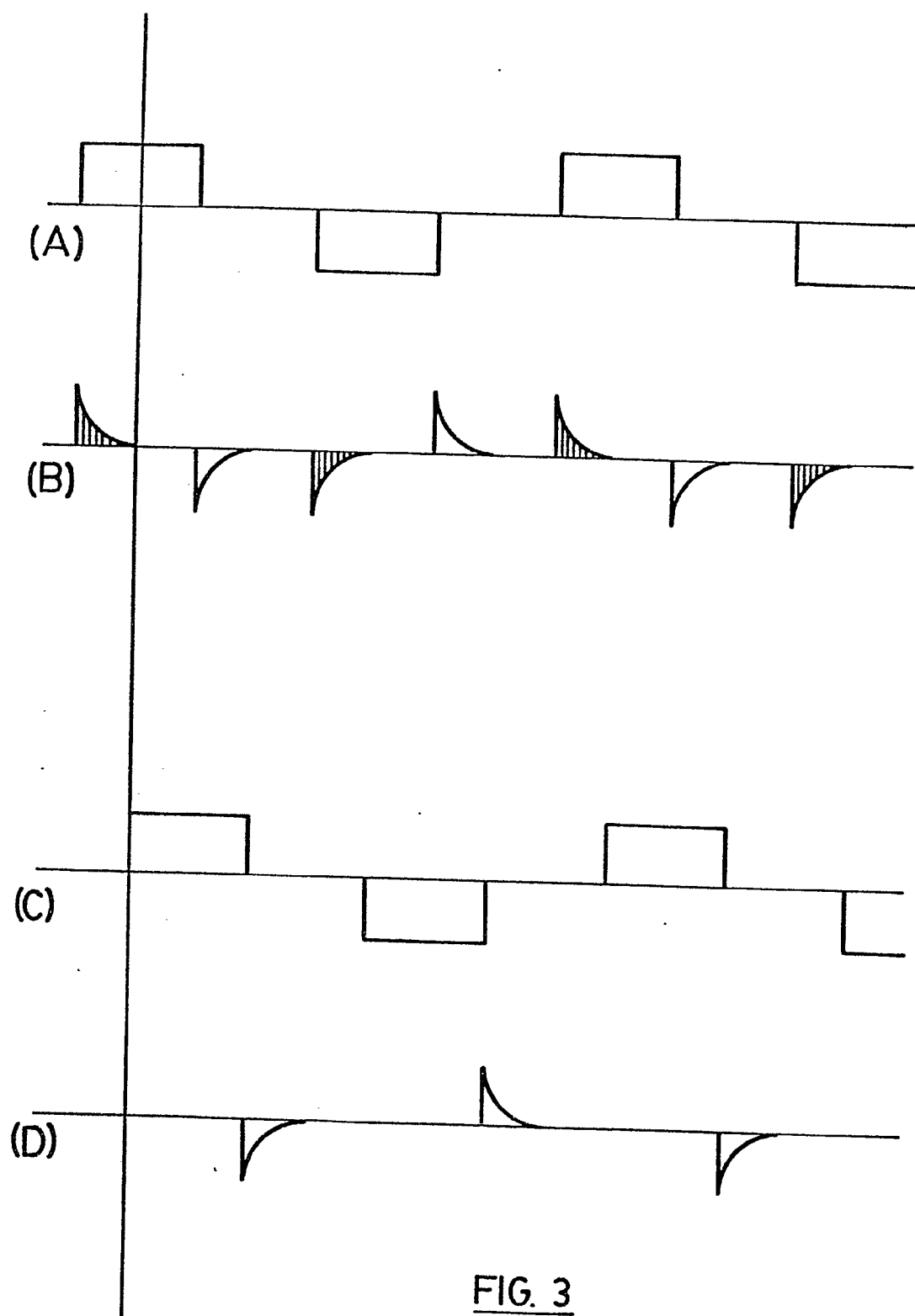ing one or more additional narrow band filters (25) each

tuned to a different higher harmonic of said fundamental
frequency, and each associated with in-phase or in-phase
and quadrature synchronous detectors (28I, 28Q) receiving
reference signals at frequencies which are multiples of
the fundamental frequency appropriate to the harmonic to
be detected, whereby to recover at least in-phase com-
ponents of at least two different harmonic components of
said secondary signal.

4.   Apparatus according to claim 3, characterised in
that it includes means (32) to determine the amplitude
difference of similarly phased outputs of detectors
associated with filters tuned to different harmonic
components, after compensation of said outputs to
eliminate frequency dependent amplitude differences.

5.   Apparatus according to any of claims 1 to 4 for
processing signals which are prerecorded, characterised in
that the apparatus further includes means (32) for
recovering secondary and reference signals from a record
of such signals.

6.   A frequency domain geophysical electromagnetic
surveying system comprising a transmitter adapted to
submit terrain being surveyed to successive abruptly
terminated magnetic fields by application of a cyclical
current waveform at the fundamental frequency with
interruptions following the termination of each field, and
a receiver gated to respond to secondary magnetic fields
generated by the terrain only during predetermined inter-
vals wholly within the interruptions, characterised in
that the receiver includes apparatus according to any of
claims 1 to 5.

FIG. 1

FIG. 2

(A)

(B)

(C)

(D)

FIG. 3